CONSULTANT REPORT

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Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally-Preferred
Advanced Generation

220 kWe SOLID OXIDE FUEL CELL/ MICROTURBINE GENERATOR HYBRID PROOF OF CONCEPT DEMONSTRATION REPORT

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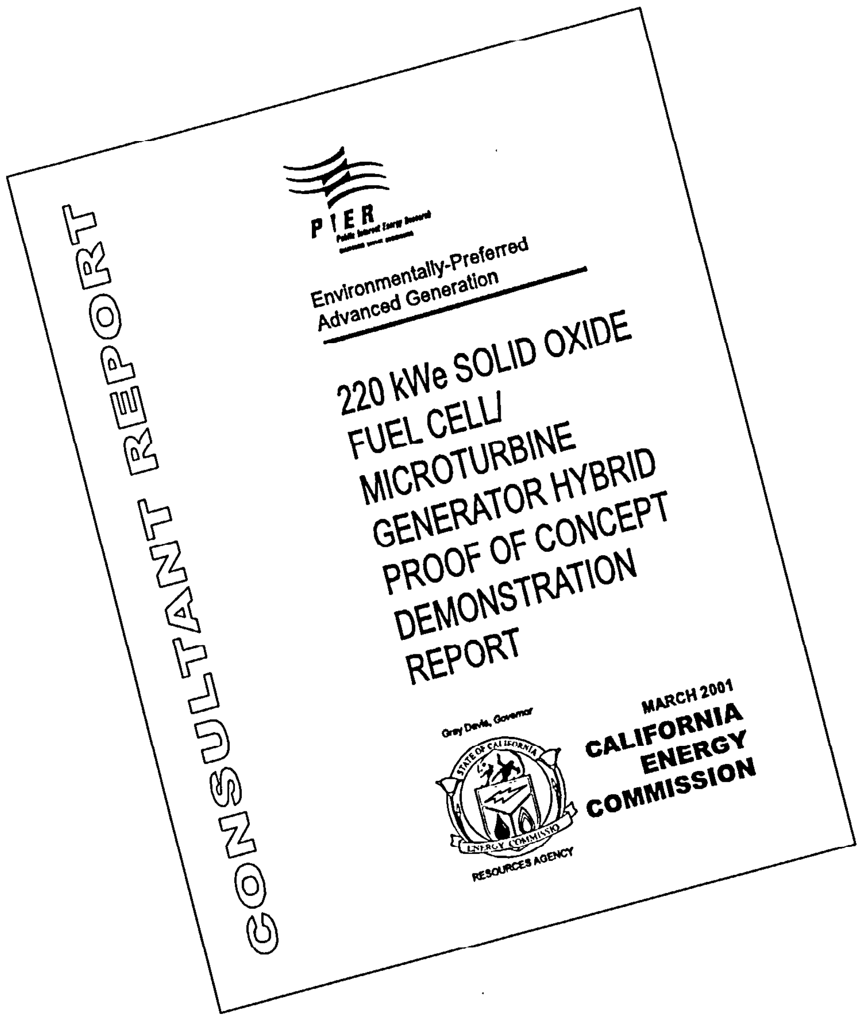

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Legal Notice

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities and public or private research institutions.

PIER funding efforts are focused on the six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Environmentally Preferred Advanced Generation
- Industrial / Agricultural Water End-Use Energy Efficiency
- Renewable Energy
- Strategic Energy Research

What follows is the final report for the 220 kWe Solid Oxide Fuel Cell / Microturbine Generator Hybrid Proof of Concept Demonstration Project, project 500-97-012 conducted by Southern California Edison Company (SCE). The report is entitled 220 kWe Solid Oxide Fuel Cell / Microturbine Generator Hybrid Proof of Concept Demonstration. This project contributes to the Environmentally Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

This report describes the Southern California Edison Company (SCE) project to demonstrate the world's first Pressurized Solid Oxide Fuel Cell module (PSOFC) and a Micro-turbine Generator (MTG) integrated power system (PSOFC / MTG).

This project is a first-of-its-kind demonstration of an integrated pressurized fuel cell and micro-turbine generator power system, often referred to as a hybrid fuel cell. The scientific and engineering community theorized that the integration of a high-temperature fuel cell such as a solid oxide fuel cell with a micro-turbine generator could result in significant improvement in electric generation efficiency, approaching 60%. The hybrid concept is that the PSOFC can supplant the MTG combustor, while the MTG provides the air source for the PSOFC. The hot air exiting the PSOFC is expanded through the MTG turbine, driving the compressor, with remaining available energy used to drive an electric generator to produce additional electric power. Additionally, fuel cells produce very little pollutant emissions.

This demonstration achieved the highest electrical efficiency of any small distributed power system, proving that small power systems (sized in hundreds of kilowatts) can achieve the efficiencies associated with large gas turbine combined cycle power systems (hundreds of megawatts).

Objectives

The project objectives and approaches taken to accomplish the objectives were:

- **Design the first PSOFC and MTG hybrid power system.** The approach taken was to contract Siemens Westinghouse Power Corporation (SWPC) to design a PSOFC and integrate it with a commercially available MTG. SWPC selected Ingersoll-Rand Energy Systems (IRES) as the MTG subcontractor.
- **Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.** The demonstration proves the concept that the PSOFC can supplant the MTG combustor, while the MTG provides the air source for the PSOFC. The approach was to contract with SWPC to construct the design resulting from the first objective. Following construction, the hybrid was demonstrated to be able to start, operate and shut down during a factory acceptance test (FAT) and a site acceptance test (SAT).
- **Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.** The approach taken is to operate the hybrid power system for 3000 hours, collecting operational data for analysis. The Commission’s involvement in this project includes operation through the site acceptance test, and does not include the entire scope of 3000 operating hours to accomplish the third objective.

Outcomes

- SWPC designed a 200-kilowatt (kW) PSOFC with process air flow and thermal exhaust that would be well suited for a 50 kW MTG. The projected design gross power was 250 kW with a design efficiency of 57% at that power. Because a 50 kW MTG was not commercially available, the project design proceeded with a commercially available but

oversized IRES 75 kW MTG. As a result of the oversized MTG, excess process air was provided to the PSOFC and the PSOFC provided less-than-design thermal energy to the MTG. The mismatch between the size of the PSOFC and MTG caused a decrease in power and efficiency from design goals.

- Detailed design and fabrication was completed during 1998 and 1999. A FAT was completed in April 2000. At the conclusion of the FAT, analysis of performance indicated that 5% of the fuel was bypassing the fuel cell stack. The impact was a further reduction in efficiency.

  A SAT was completed in two parts. In part 1, the hybrid power system was relocated from the factory to the test site in May 2000, and restarted in June. After 154 hours of operation, a power lead failed, causing an automatic shutdown. Some of the fuel bypassing the fuel cell stack was burning in the PSOFC pressure vessel near the power leads, causing overheating. The PSOFC skid was returned to SWPC for disassembly, inspection and repair. After disassembly and inspection, the stack liner and the power leads were redesigned and re-fabricated to correct the fuel bypass problem. The system was returned to the test site in December 2000. In part 2 of the SAT, the system was restarted in January 2001 and operated for 514 hours. SWPC directed manual shutdown in mid February due to an observed deterioration in Row 2 voltage. The PSOFC skid was returned to SWPC for warranty repair.
- During operations in June 2000 and January and February 2001, the hybrid power system proved the concept that the PSOFC can supplant the MTG combustor, while the MTG provides the air source for the PSOFC. The system performance met most of the acceptance criteria, and was conditionally accepted by Southern California Edison on January 13, 2001.

Conclusions

Although this project proved the concept of the “hybrid” fuel cell and microturbine power system, and set records for fuel cell power system efficiency, the design of the integrated PSOFC / MTG power system was not optimal because of the unavailability of a commercial 50 kW MTG. Future projects should increase the fuel cell stack size and rating to better match commercially available MTGs.

The design included provision to “dump” the generated Direct Current (DC) and Alternating Current (AC) power into load banks to prevent grid fluctuations and upsets from disturbing the demonstration. This project should be funded for retrofit of a DC-to-AC inverter system and continued operation to demonstrate the efficiency and reliability of the inverter system to provide useful power throughout the range of operating voltages and currents generated by the PSOFC / MTC power system. Future system designs should include useful electric loads and demonstrate grid connection capabilities of the MTG-generated power.

Low Row 2 voltage resulted in less than design DC stack power. Replacement of deficient cells is in progress. No further corrective action is recommended.

At the time that this system was designed, a single-shaft MTG was not available and a two-shaft design was used. The two-shaft MTG design contributed to diurnal variations in stack temperature. These variations required limited human supervision and operation to maintain stack temperature in the design operating range. A commercial hybrid power system will need to implement better steady state controls to support unmanned operation. Future system designs might use single shaft MTGs with power inverters able to control the electric load on the MTG. Through operating system control of MTG load, the MTG speed and compressor air flow may be used to automatically maintain fuel cell stack temperature.

Abstract

This report describes the Southern California Edison Company (SCE) project to demonstrate the world's first Pressurized Solid Oxide Fuel Cell module (PSOFC) and a Micro-turbine Generator (MTG) integrated power system (PSOFC / MTG).

This project is a “Proof of Concept” demonstration for a PSOFC / MTG integrated power system. The concept to be proven is that the thermal energy by-product from a PSOFC can be used as the thermal energy source to drive an MTG while the MTG compressor is used as the air supply for the PSOFC.

By pressurizing the fuel cell, its electrical generation capacity increases by approximately 40%. The hot air exiting the PSOFC is expanded through the MTG turbine, driving the compressor, with remaining available energy used to drive an electric generator to produce additional electric power.

This project is partly funded under the Public Interest Energy Research (PIER) transition program. The report includes discussion of the design and construction, factory acceptance tests and site acceptance tests. The California Energy Commission provided co-funding through site acceptance testing.

The specific project objectives were:

- **Design the first hybrid PSOFC and MTG integrated power system.** The process of designing the hybrid power system accomplishes the detailed engineering required to integrate the PSOFC and MTG.
- **Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.** The demonstration proves the concept that the PSOFC can supplant the MTG combustor, while the MTG provides the air source for the PSOFC.
- **Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.**

Siemens Westinghouse Power Corporation (SWPC) designed and constructed the PSOFC, and Ingersoll-Rand Energy Systems (IRES), formerly Northern Research and Engineering Corporation, designed and constructed the MTG. The integration design was conducted by SWPC. SWPC fabricated the PSOFC and developed integrated power system control software. IRES fabricated the MTG, including startup combustors, recuperator, and MTG controls. SWPC completed final fabrication integrating all components. Factory tests were conducted by SWPC at the manufacturing site in Pittsburgh, PA. SCE’s final acceptance test was conducted at the University of California at Irvine (UCI), SCE’s selection for the demonstration. While at UCI, the PSOFC / MTG is planned to operate for 3000 hours beyond the site acceptance. Continued testing beyond site acceptance is outside the scope of the Commission work. SCE has agreed to provide a copy of the final report to the Commission at no cost. The final report will be completed in 2002.

Keywords: Hybrid, Solid oxide fuel cell, High temperature fuel cell(s), Southern California Edison, Siemens Westinghouse

1.0 Introduction

1.1 Background and Overview

This project supports the California Energy Commission's Public Interest Energy Research (PIER) program to help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. In addition, the effort contributes to the U. S. Department of Energy's (DOE's) Fossil Energy Program entitled Vision 21, the goal of which is to develop small electric generating systems capable of 70% energy efficiency.

This project is a first-of-a-kind demonstration of an integrated pressurized fuel cell and micro-turbine generator power system, often referred to as a hybrid fuel cell. The demonstration achieved the highest electrical efficiency of any small distributed power system. The measured electrical efficiency is equal to the state-of-the-art combined cycle gas turbine power system.

Fuel cells are small electric generators with high efficiencies, approaching 50%, and close to commercialization. Micro-turbine generators (MTGs) are small generators with efficiencies approaching 30%, and currently in commercial production. The scientific and engineering community theorized that the integration of a high-temperature fuel cell (such as a solid oxide fuel cell) with a micro-turbine generator could result in significant improvement in electric generation efficiency, approaching 60%, and with technology improvements, even higher efficiencies.

This hybrid fuel cell demonstration has proved that small power systems sized in hundreds of kilowatts (kW) can achieve the high efficiency found in large gas turbine combined cycle power systems of hundreds of megawatts. Smaller power systems are suitable for distributed generation applications, electric power generated close to the end user.

The fuel cell and micro-turbine generator integration concept uses the high-temperature thermal energy exhausted from a solid oxide fuel cell as the thermal energy source to supplant the MTG combustor. The MTG compressor provides the air supply for the solid oxide fuel cell. With pressurization, fuel cell electrical generation capacity is increased by approximately 40% compared to an un-pressurized fuel cell. The thermal energy produced by Pressurized Solid Oxide Fuel Cell (PSOFC) generation is removed by air flowing through the PSOFC. The hot air exiting the PSOFC is expanded through the MTG turbine, driving the compressor; with remaining available energy used to drive an electric generator to produce additional electric power. The operation of the two generators together has a combined effect to produce more electric power than either operating alone. Additionally, fuel cells generate electricity with very little pollutant by-products.

Siemens Westinghouse Power Corporation (SWPC) was contracted to design the PSOFC and integrated power system. SWPC subcontracted Ingersoll-Rand Energy Systems (IRES) to design the MTG system.

This project designed, built and operated the world's first integrated fuel cell and micro-turbine generator power system.

Figure 1. The SWPC 220 kW PSOFC/MTG

1.2 Project Objectives

- **Design the first hybrid PSOFC and MTG integrated power system.** The process of designing the hybrid power system encompasses the detailed engineering required to integrate the PSOFC and MTG. Important design goals were to:
  - Increase the power of a 140 kW direct current (DC) atmospheric solid oxide fuel cell to 200 kW by raising operating pressure from 1 atmosphere (absolute) to 3 atmospheres, and operating at a nominal temperature of 1000 degrees Celsius.
  - Accomplish fuel cell pressurization using compressed air from a commercially available 50 kW MTG, operating at a pressure ratio of approximately 3 to 1 with a turbine inlet temperature between 800 and 900 degrees Celsius.
  - Design the reconfiguration of the MTG: the recuperator exhausting to the PSOFC through a stack heating combustor, and PSOFC exhausting to the MTG combustor. Combustor operation would be required only during system startup.
  - Design the PSOFC pressure vessel and process air flow paths through the vessel.
  - Specify the methods for operation and control, including integration of the PSOFC control computer and MTG control computer.
- **Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.** The demonstration proves the concept that the PSOFC can supplant the MTG combustor, while the MTG provides the air source for the PSOFC. The Commission is involved with this project through the site acceptance test (SAT). After site acceptance at the University of California at Irvine (UCI), the

PSOFC / MTG will be operated for an additional 3000 hours. This additional testing is outside the scope of the Commission. Southern California Edison Company (SCE) has agreed to provide a copy of the final report to the Commission at no cost. The final report will be completed in 2002.

An additional objective should be completed during testing beyond the scope of the Commission's involvement in this project.

- **Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.**

2.0 Project Approach

The approach taken to accomplish the objectives was to assign and perform specific tasks for each objective.

- **Design the first PSOFC and MTG hybrid power system.** To accomplish the first objective, SWPC was contracted to design the PSOFC and integrated power system. SWPC subcontracted IRES to design the MTG system.
- **Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.** To accomplish the second objective, SWPC was contracted to fabricate the PSOFC and assemble the integrated power system. SWPC subcontracted IRES to fabricate the MTG system. Startup, operation and shutdown were to be demonstrated for 100 hours in a factory acceptance test (FAT) prior to relocation to the SCE test site for continuing operation and demonstration. Following relocation to the test site, an additional 100 hours of operation were to be conducted prior to SCE's final acceptance, in a site acceptance test (SAT).
- **Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs. T**o accomplish the third objective, continuing operation at the SCE demonstration site is to be conducted for 3000 hours (outside the scope of this project). The design of the integrated power system incorporates sufficient instrumentation and automatic data recording to capture the important operating parameters to characterize operational performance. During operation, power system data is downloaded daily by SWPC for performance analysis.

3.0 Project Outcomes

Design the first PSOFC and MTG hybrid power system.

The original design goal for the PSOFC was to produce 200 kW DC gross power at an operating pressure of 3 atmospheres (absolute) and operating temperature of 1000 degrees Celsius. The nominal airflow rate and thermal energy from the PSOFC was calculated to be sufficient for a 50 kW MTG. A design goal was established for the MTG to produce 50 kW gross 3-phase alternating current (AC) power at 60 Hz and 480 VAC phase to phase. The combined unit output would be 250 kW.

Because a 50 kW MTG was not commercially available, the project proceeded with an available MTG with greater than optimum size. SWPC engineers and SCE recognized that with an oversized MTG, optimum performance would suffer. The oversized MTG would provide excess airflow for the PSOFC and the PSOFC would provide less than optimum thermal energy for the MTG. The final SWPC PSOFC / MTG system design for this project consisted of a Solid Oxide Fuel Cell (SOFC) tubular fuel cell stack within an ASME coded pressure vessel mated with a repackaged and de-rated IRES 75 kWe PowerWorks MTG. The system was constructed on two skids:

- The Generator / Fuel Supply System (GEN / FSS) skid containing the PSOFC pressure vessel and fuel supply system, and
- The Thermal Management System (TMS) skid containing the MTG, recuperator, startup combustors and electrical distribution and control systems.

The PSOFC stack consists of 1152 vertically mounted tubular cells operating in a series / parallel configuration. The stack is arranged in 12 rows, each containing four bundles of 24 cells. A bundle is shown in Figure 2. A cell cross section is shown in Figure 3. Each cell is 1500 millimeters long and 22 millimeters in diameter. Each bundle of 24 cells is connected in series parallel to provide cumulative voltage of eight cells in three parallel conducting paths. At design conditions, cell current will be approximately 250 amps (750 stack amps).

Figure 2. SOFC Tube Bundle

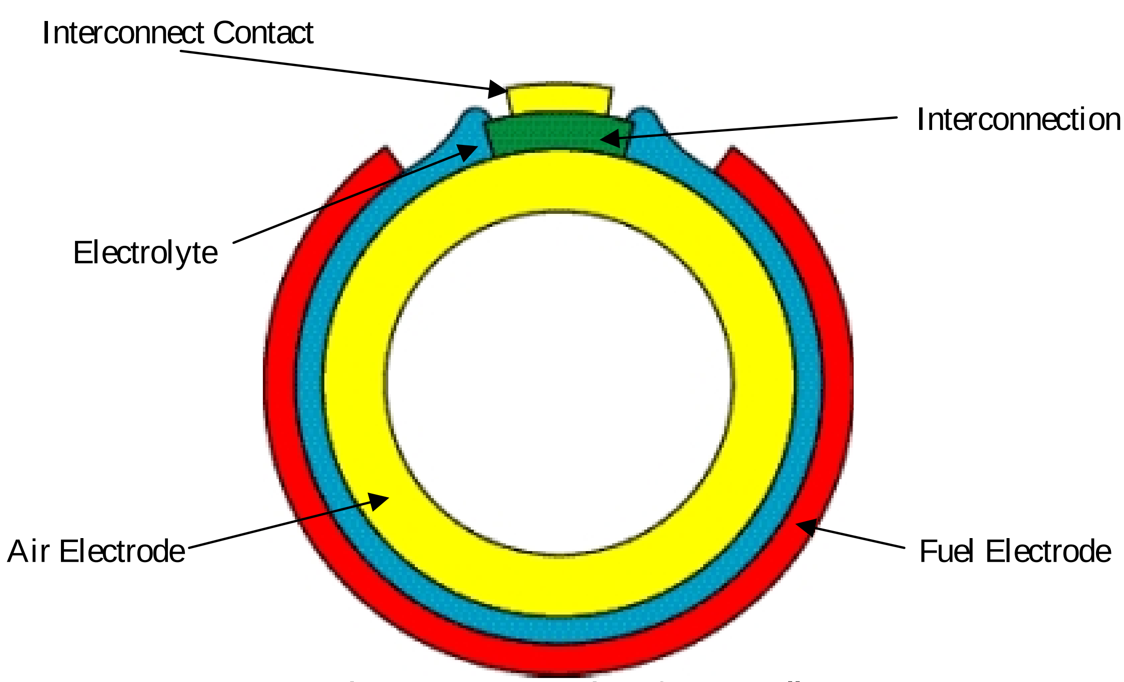


Figure 3. Cross-Section of SOFC Cell

This stack configuration is designed to develop approximately 140 kWe (DC) operating at atmospheric pressure. Operating pressurized, the rated power of the stack is increased significantly and is expected to achieve 180 kWe to 200 kWe DC gross output.

The IRES MTG is a two-shaft turbine system. A radial centrifugal compressor and a radial inflow turbine are on a common shaft, referred to as the Gasifier. A radial inflow free power turbine on the second shaft drives a synchronous AC generator through reduction gear.

For this project, the power generated by both devices (PSOFC and MTG) is dissipated in resistor load banks. This avoids added complications to the testing process caused by grid fluctuations or outages. A simplified process flow diagram is shown in Figure 4.

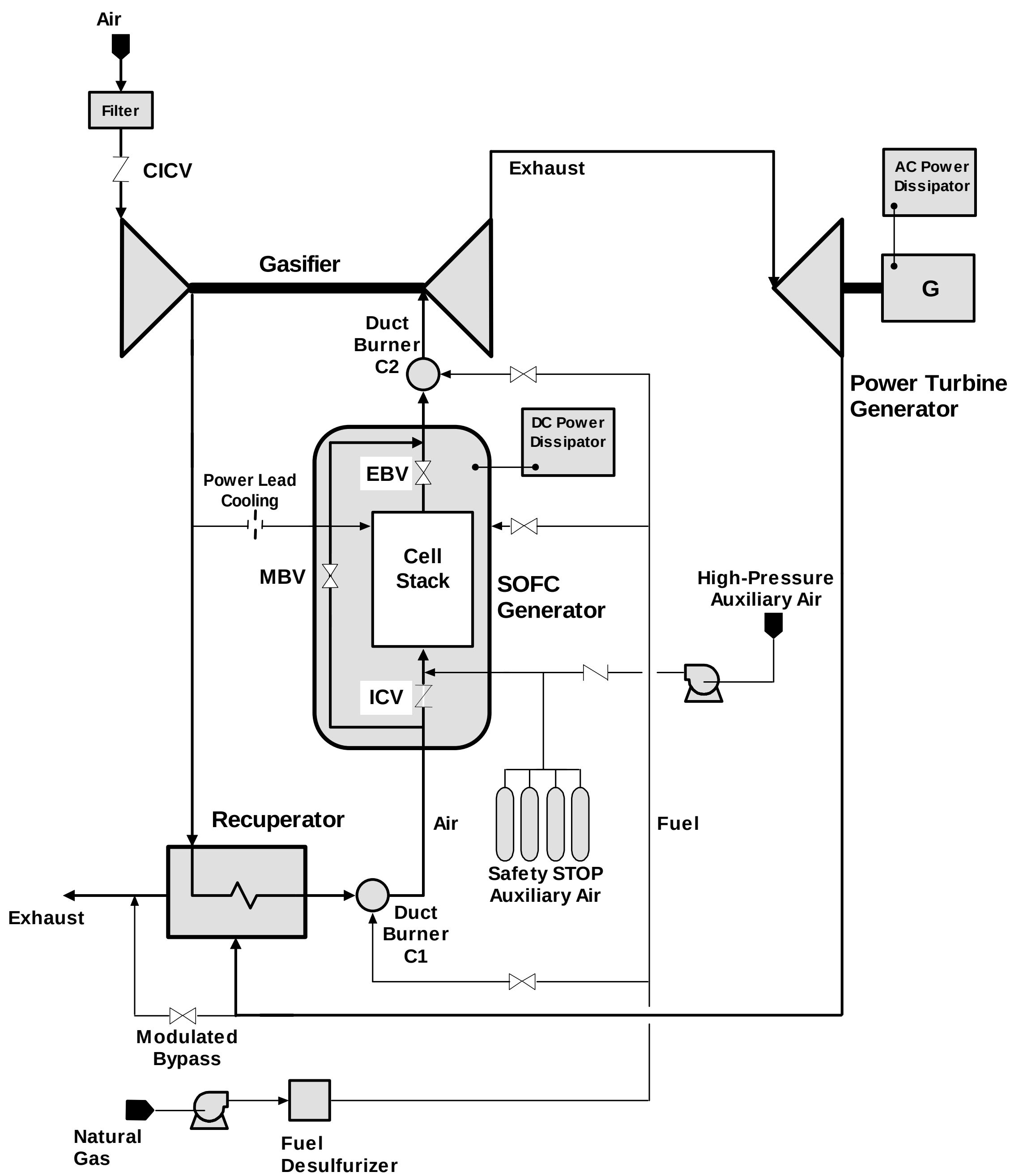


Figure 4. Simplified PSOFC/MTG Schematic

During normal steady state operation, the cell stack operates at a maximum of 1000° C, and is pressurized to approximately three atmospheres (absolute) by the Gasifier's compressor. The Gasifier provides process airflow that is heated by compression and further heated to approximately 550° C by a recuperator heat exchanger prior to discharging into the PSOFC pressure vessel. The process air is further heated by the SOFC generator, which supplants the need for a turbine combustor.

The process air is delivered at pressure to the Gasifier. Process air from Gasifier exhaust at intermediate pressure provides the motive power to spin the Power turbine, which develops an additional 20 kWe to 30 kWe AC power. The process air at the Power turbine exhaust has remaining thermal energy (at low pressure), a portion of which is transferred to PSOFC inlet air in the recuperator.

During steady state operation, process air is delivered to the Gasifier in the temperature range of 700 to 800° C, lower than the IRES nominal design inlet temperature (TIT) of 871° C. This low temperature is the result of the design to accommodate a larger-than-nominal 50 kW MTG. The process air exiting the pressure vessel mixes with excess air bypassing the pressure vessel. The resultant temperature is reduced, which is why the 75 kWe MTG provided less than its design output.

The system also contains two natural gas fired combustors, which are used during startup. The "C1" combustor provides stack heating and the "C2" combustor provides energy to the MTG during startup of the integrated system. The C2 combustor is operated until the process air temperature from the PSOFC is sufficient to maintain turbine operation, and the C1 combustor is operated until the PSOFC is generating sufficient thermal energy to maintain stack temperature.

Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.

Construction of the integrated system design was completed in October 1999, and preliminary operational tests were conducted between November 1999 and January 2000 with the GEN / FSS skid and TMS skid connected, but without the SOFC stack installed. The preliminary tests were conducted to validate control algorithms developed to ensure that the programmable logic computers operated correctly for startup, shutdown and "upset" conditions. Following preliminary testing, the SOFC stack was installed in the pressure vessel in preparation for the FAT.

Factory Acceptance Test (FAT) -- During the FAT, the following were accomplished:

- A normal startup
- An inadvertent stop
- A manually initiated turbine stop and recovery
- Operation for 110 hours
- An erroneous turbine stop in lieu of a normal stop

The FAT began on April 1, 2000 and ended on April 8, 2000. Table 1 summarizes the event chronology during the FAT.

Table 1. FAT Chronology of Events

Date	Observation/Time	Measurements and Calculations
April 1, 2000	Start at 300°C @ 9:00 a.m.	Generator current reaches 100A @ TG2= 800°C.
April 2	Enter RUN @ 9:38 a.m.	Generator current reaches 405 amps @ TG2= 1000°C.
April 3	In RUN, GENIDC reaches 600 amps.	
April 4	Generator current was increased to 630 amps and flame out of C1 burner occurred at 9:00 a.m. An unscheduled STOP occurred at 11:56:42 during a fuel-balancing maneuver. At 13:55 the unit was manually sent to TSTOP to slow the cool down. By midnight, the generator current had again reached 500 amps.	
April 5	By 11:00 a.m., the current reached 660 amps and C1 burner was turned off.	
April 6	By the end of this day, the generator current was raised to 675 amps.	
April 7	In a.m., GENIDC was increased to 700 amperes. At noon a scheduled STOP was initiated from the keyboard. One minute later, the compressor surged and the system automatically moved the unit to the TSTOP state. The operators decided to cool the unit using only the HPAA.	110 hours in RUN during FAT.
April 8	The NHMIX was turned off at 12:03.	

During the FAT, the unit accumulated 110 hours in the RUN state (PSOFC generator current greater than 300 amps), and 17 MW-hrs of electric power were generated. The following are key measurements and calculations determined during the FAT:

Terminal Volts = 238.3 VDC
Generator Current = 700.8 Amps
PSOFC DC Gross Power = 165.6 kWe
MTG AC Gross Power = 22 kWe
Equivalent Net AC Power = 175.5 kWe
System Equivalent AC Efficiency = 49.1%

Notes:

- Equivalent Net AC Power assumes a DC to AC conversion efficiency of 94% and an auxiliary parasitic load of 2 kWe.
  Equivalent Net AC Power = 0.94*165.6 + 22 – 2 = 175.5 kWe
- System Efficiency is the ratio of Equivalent Net AC Power to the energy content of the fuel flow rate, based on the lower heating value at 0 degrees Centigrade.
  System efficiency = 175.5 kW / (1250 SCFH * 976 BTU / SCF) * 3413.4 BTU / kW-hr) = 49.1%.

Figure 5 shows PSOFC DC power, MTG AC power, PSOFC Temperature, Ambient Temperature and Equivalent AC Efficiency during the FAT.

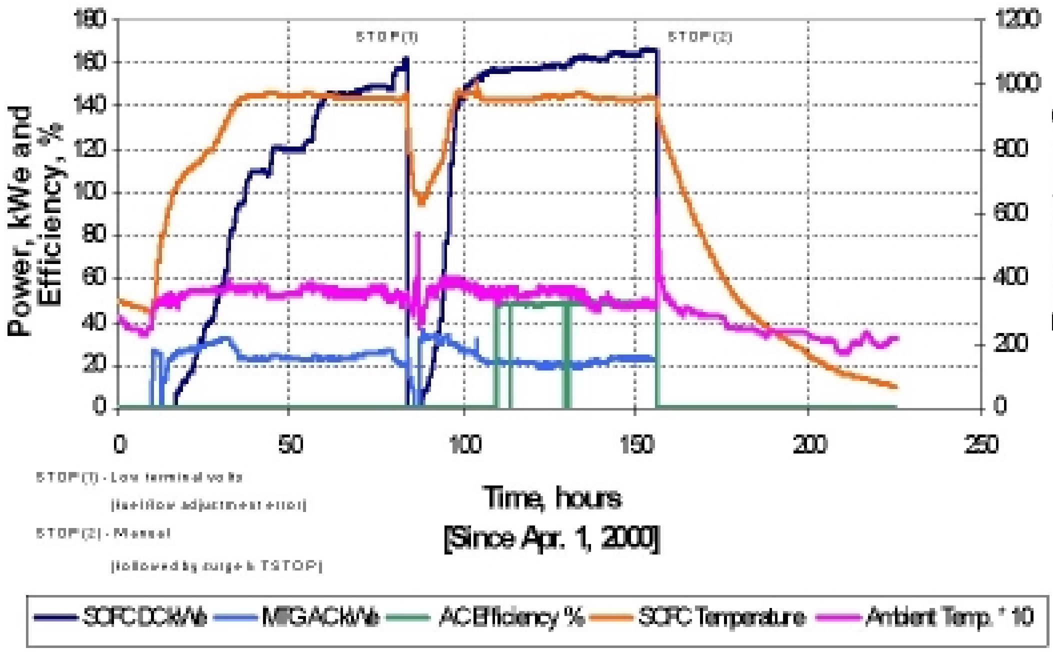


Figure 5. Operating Parameters During FAT

During the FAT, the equivalent AC efficiency was lower than expected. It was determined that this problem was caused by fuel-bypass. Fuel-bypass is supplied natural gas, which does not contact the cells as it passes through the system. Fuel utilization is the percent of fuel consumed by the stack. Analysis of fuel use and compositions entering and exiting the stack led to the assessment that approximately 5% of the total fuel flow was bypassing the stack. The problem was not deemed sufficiently severe to disassemble the PSOFC to investigate.

Following completion of the FAT, the PSOFC / MTG was prepared for shipment to the SCE test site at UCI, where it was delivered in May 2000.

Installation at the site was completed during May 2000. Attachment 1 includes photographs of support systems installed at the site. Attachment 2 includes photographs of the PSOFC and TMS skid installation.

Site Acceptance Test (SAT) -- The SAT was started in June 2000, but aborted due to a power lead failure. The PSOFC skid was returned to SWPC in Pittsburgh to conduct repairs, and did not return to the UCI test site until December. Restart was conducted on January 8, 2001, and Site Acceptance completed January 13, 2001. Operations continued through January 18, 2001, when a “spurious” TSTOP occurred; the indicated problem was speed of the power turbine. Corrective action was completed January 23, 2001, and restart was conducted January 29, 2001. Operations continued until February 11, 2001, when SWPC directed suspension of operations due to deteriorating Row 2 voltage.

Table 2 summarizes the event chronology during the SAT.

Table 2. SAT Chronology of Events

Date	Observation/Time	Measurements and Calculations
June 3, 2000	Transition from PREOP to HEAT. At 575°C transition from HEAT to LOAD.	Slow heat-up rate due to restricted C1 exit temperature.
June 4	At 900°C transition from LOAD to RUN.	
June 6	Extinguish C1 combustor. MTG supported by PSOFC thermal.	IGEN = 645 amps. IGEN increased to 665 amps for cell conditioning.
June 11	Automatic STOP, Low Terminal Voltage.	Low Terminal Volt measurement caused by power lead failure 153 hours in RUN from June 3.
July 10	GEN/FSS Skid departs Test Site.	Power lead failure requires factory repair.
December 14	GEN/FSS Skid returns to Test Site.	
January 8, 2001	Transition from PREOP to HEAT. At 575°C transition from HEAT to LOAD.	C1 combustor achieves rated thermal output, exit temperature of 800°C.
January 8	At 900°C transition from LOAD to RUN. Approximately 9.5 hours total in LOAD.	
January 10	Extinguish C1 combustor.	IGEN = 645 amps. IGEN increased to 680 amps.
January 13	Automatic STOP, Lo-Lo SSAA pressure. One minute later, the compressor surged and the system automatically moved the unit to the TSTOP state.	SSAA pressure switch actuated above proper set point. Event occurred at 1:20 a.m.
January 13	Recovery from STOP complete.	IGEN = 680 amps at 2:30 p.m. SCE (conditionally) accepts unit.
January 13	Complete Site Acceptance.	SCE Accepts PSOFC/MTG, Site Acceptance Criteria complete with exceptions.

Date	Observation/Time	Measurements and Calculations
January 18	Automatic TSTOP.	Power turbine over speed indicated cause of trip. Event occurred at 8:00 p.m. 227 hours in RUN from January 8, 2001.
January 23	TSTOP corrective action complete. In PREOP state.	
January 29	Transition from PREOP to HEAT. At 575°C transition from HEAT to LOAD.	Restart after TSTOP.
January 30	At 900°C transition from LOAD to RUN, extinguish C1 at 645 amps.	Increase IGEN to 680 amps.
February 1	Continue operating.	Increase IGEN to 710 amps.
February 11	Shutdown, keyboard initiation of TSTOP.	Row 2 voltage deteriorating, 2 VDC lower than average row. 514 hours in RUN from January 8, 2001.

SAT (Part 1)

On June 3, 2000, startup began. The new C1 combustor was unable to provide the design 800° C exit temperature without exceeding internal plate temperature specifications. Exit temperature was maintained below 740° C, but the result was a slow heatup lasting 30 hours. On June 4, the unit was placed in RUN at 900° C, and operators began incrementing current in 5 amp steps. On June 6, C1 was allowed to extinguish at 645 stack amps output. Output was increased to 665 amps and kept at that level for cell conditioning.

At 10:12 a.m. on June 11, the PSOFC / MTG entered the STOP state due to low terminal voltage. SWPC began an analysis of remotely downloaded operating data to determine the cause of the low indicated terminal volts, and determined that the cause of the STOP was most likely due to a power lead problem. On June 20, the pressure vessel head was removed, and boroscope inspections of the power leads were conducted. The inspections showed that the negative power lead was badly damaged, and some oxidation of the positive lead was evident. The PSOFC skid was shipped to SWPC Pittsburgh, PA on July 10 for additional inspection and repair. At the time of the STOP, the unit had 153 hours of operation in RUN at the SCE test site.

Figure 6 shows PSOFC DC power, MTG AC power, PSOFC Temperature, Ambient Temperature and Equivalent AC Efficiency during the SAT (Part 1).

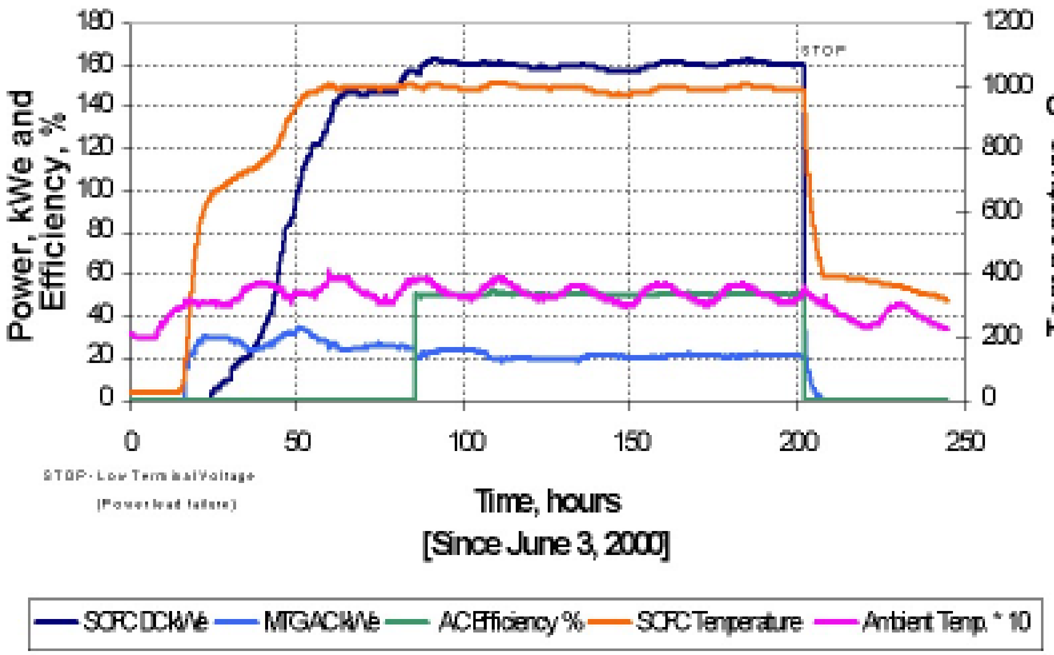


Figure 6. Operating Parameters During SAT Part 1

After return to SWPC, the PSOFC was removed from the pressure vessel. Additional inspection after disassembly revealed the negative lead failure actually achieved full separation, and the positive power lead was severely oxidized. The root cause of the power lead overheating was fuel bypass combusting in several void spaces in the insulation outside of the stack liner and inside the pressure vessel. Corrective action included redesign, fabrication and replacement of the power leads and power lead cooling system, and redesign, fabrication and replacement of the stack liner. Site modifications were made to provide supplemental power lead cooling air if required, and backup power lead cooling using site air or stored nitrogen in the event of a turbine failure. The turbine compressor is the normal source for power lead cooling air flow.

Additionally, the C1 combustor was returned to IRES, the manufacturer, for evaluation. IRES modified the combustor by altering the combustor liner to provide additional cooling for the combustor head.

Repairs were completed, and the PSOFC skid was returned to the UCI site on December 14. Re-installation was completed December 19, 2000.

SAT (Part 2)

On January 7, 2001, pre-start checklists were completed, and heat-up of the unit began on January 8. At 2:10 p.m., the operating state was changed from HEAT to LOAD, and operators began drawing current from the generator. At 11:38 p.m., generator current was greater than 300 amps, and generator temperature was over 900° C; the operating state was changed from LOAD to RUN. Throughout January 9, generator current was slowly raised, and by the morning of January 10, current exceeded 600 amps. Current was raised in several five-amp steps to 645 amps, and C1 was extinguished. By 12:41 p.m., generator current was set to 680 amps.

At 1:20 a.m. on January 13, the operating mode changed from RUN to STOP automatically due to activation of a “lo-lo” pressure switch in the safety stop auxiliary air (SSAA) system. This switch set point is nominally 1850 pounds per square inch (psi), but activated with an applied pressure of 2150 psi. The “lo” pressure switch for this system, with a set point of 2080 psi, did not activate. Shortly after entering STOP, the unit entered TSTOP due to a compressor surge. The STOP logic for the SSAA lo-lo pressure switch was changed to require activation of both the lo and lo-lo pressure switches to cause a STOP. SSAA air cylinders were changed, with cylinders fully charged to 2600 psig. At 4:15 a.m., the operating state was changed from TSTOP to COOL, and at 05:30 a.m. changed again from COOL to HEAT. At 06:00 a.m., the operating state was changed again from HEAT to LOAD, and by 10:45 a.m. the RUN state was entered. By 2:30 p.m., C1 was extinguished and by 2:45 p.m. generator current was back up to the previous 680 amps set point.

During the SAT, the unit accumulated 153 hours (June 3 to June 11, 2000) and 514 hours (January 8 to February 11, 2001) in the RUN state (PSOFC generator current greater than 300 amps), and 25 MW-hrs and 84 MW-hrs of electric power were generated.

The following are operating parameters and calculations on February 1, 2001:

Terminal Volts = 244.3 VDC
Generator Current = 702.9 Amps
PSOFC DC Gross Power = 171.7 kWe
MTG AC Gross Power = 22 kWe
Equivalent Net AC Power = 181 kWe
System Efficiency = 52.1 %

Figure 7 shows PSOFC DC power, MTG AC power, PSOFC Temperature, Ambient Temperature and Equivalent AC Efficiency during the SAT (Part 2).

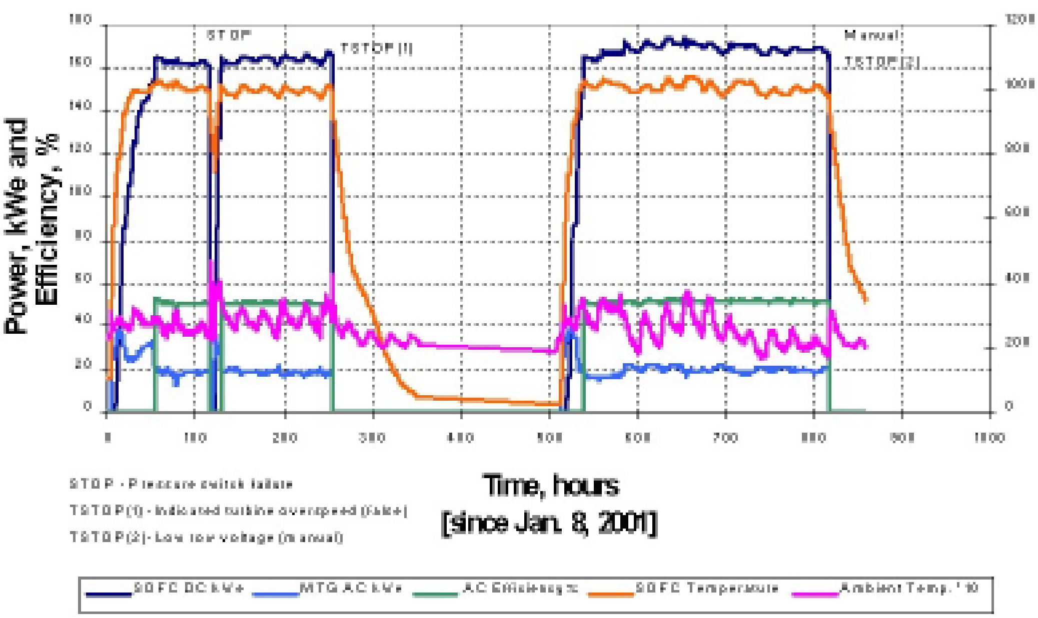


Figure 7. Operating Parameters During SAT Part 2

During operations on January 10 through January 12, gas chromatography analysis of fuel composition in and out of the fuel cell was used to determine fuel utilization. This analysis compared favorably with fuel utilization calculated from measured fuel flow and DC power. The assessed "fuel bypass" was less than 1 percent of total fuel flow. During all operations subsequent to the January 8 restart, power lead temperatures have been observed to be stable.

During system heating on January 9, C1 performance was verified to meet design values achieving an exit temperature of 800° centigrade, and during the startup on January 29, heat-up to operating temperature was completed in 20 hours.

On February 11, SWPC directed that the PSOFC be shut down due to concern over deteriorating voltage in Row 2. The shutdown and cool-down was begun by keyboard initiation of a TSTOP from the Operator Interface Control Computer. On February 24 the PSOFC skid was returned to SWPC to replace Row 2.

Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.

Objective 3 is incomplete and will continue during 3000 hours of continued operation following replacement of Row 2. Operation through the SAT has already provided significant information on the performance characteristics of the integrated design and identification of problem areas to be addressed in follow-on project designs. Conclusions and recommendations based on that information are included in this report.

In addition, this hybrid PSOFC / MTG power system has operated, with minor exceptions, within the design criteria. The system has provided sufficient information for SWPC, in conjunction with DOE, to commit to the manufacture of two 300 kW-class hybrid systems in Europe and two 1,000 kW-class Hybrid systems; one in the United States and another in Europe.

4.0 Conclusions and Recommendations

4.1 Conclusions

Design the first PSOFC and MTG hybrid power system.

The design of the integrated PSOFC / MTG power system was not optimal because of the unavailability of a commercial 50 kW MTG. The only available MTG was too large, resulting in excess air flow. The design accommodated the excess air flow by including a PSOFC module bypass valve to route the excess air around the PSOFC. The bypassed air, when mixed with air exiting the PSOFC, significantly lowers the MTG air inlet temperature, resulting in poor MTG performance. The MTG developed only 22 kW during operations to date.

The design included provision to "dump" the generated DC and AC power into load banks. The final MTG design included an AC synchronous generator. The ability to control the frequency to parallel with the grid was not proven. Varying the resistance of the load bank ultimately controlled the power turbine speed. The demonstration would be more complete if the power generated were provided to a useful site load, or exported in parallel with the grid. This would determine the durability of the power system to withstand grid upset conditions. Additionally, a more complete design would include the conversion of DC to AC for the PSOFC, and grid paralleling capabilities for the MTG.

Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.

The unit was successfully built, started and operated. The concept was demonstrated that the PSOFC can provide adequate thermal energy to supplant the MTG combustor, and simultaneously the MTG compressor can provide air flow for the SOFC at pressure, resulting in increased SOFC power. Operations to-date have set SOFC records for power and efficiency.

Low Row 2 voltage resulted in less-than-design DC stack power, 180 kW as a minimum and 190 to 195 kW as a goal. With reduced PSOFC power, less thermal energy was provided to the MTG with a resultant lower MTG power generation.

Following recovery from STOP on January 13, the unit completed 100 hours of operation. Not all of the acceptance criteria were met, but SCE conditionally accepted the unit on this date. The following were the modifications to the acceptance criteria as accepted:

- 100 hours of operation at the test site, achieved this criteria on January 13, 2001.
- 180 kWe of DC power generation from the PSOFC (200 kW nominal); as of January 13, only 166.5 kW DC was achieved. Design power was not achieved due to low stack voltages, Row 2 being the limiting row. This problem is expected to be resolved after currently progressing repairs to the stack are completed.
- 47% DC efficiency, achieved 52% equivalent AC efficiency and 49% DC efficiency.
- Emissions of less than 5 ppm oxides of nitrogen (NOx), achieved this criteria at FAT (measured less than 1 ppm). Additionally, a certified South Coast Air Quality Management District (SCAQMD) test will be conducted following return of the unit after repair of Row 2.
- Demonstration of the ability to start up and shut down was achieved.

- Demonstration of the ability to shut down safely during "upset" conditions, achieved this criteria by successfully handling three unplanned automatic shutdowns (without damage), proving the ability of the control system to safely shut down the unit.
- Demonstrate the ability to operate at 50% of full power, achieved this criteria during start up. Continued steady operation at 50% of full power will, however, require "firing" the natural gas combustor, since the fuel cell operating at 50% power cannot produce sufficient thermal energy to operate the micro-turbine.

Although not a requirement for site acceptance, an original design goal was to achieve an equivalent AC efficiency of 57% or higher. This was not achieved because low Row 2 voltage limited PSOFC power, a resultant reduction in MTG power with less energy provided from the stack, and excess MTG air bypassing the stack and lowering turbine inlet temperature. The peak equivalent AC efficiency observed in operations through the SAT was 52%.

Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.

Operations and operational failures to date have already resulted in design improvements. Specifically:

- The stack liner was redesigned and re-fabricated to nearly eliminate fuel bypass. The fuel bypass was the root cause of overheating and failure of a power lead.
- The power lead cooling system was modified to provide continuous cooling air from alternative supplies in the event of a turbine failure. The turbine compressor is the normal supply for power lead cooling air.
- The instrumentation and control system was modified to include additional power lead temperature indication and added a power lead high temperature alarm function.

To date for this project, steady state operation requires limited human supervision. A commercial PSOFC / MTG system will need to implement better steady state controls to support unmanned operation.

The use of a two-shaft MTG has contributed to diurnal variations in stack temperature. The Gasifier turbine speed, and resultant compressor air flow, are "controlled" with turbine inlet temperature and firing of the C2 combustor. Higher C2 exit temperatures provide more energy to the Gasifier turbine, increasing turbine speed and increasing compressor air flow. When C1 and C2 are extinguished, the PSOFC-rejected thermal is the energy source for the Gasifier turbine. In this operating mode, ambient temperature has been observed to have a significant impact on PSOFC temperature. As ambient air temperature increases, the air density decreases. The MTG compressor, at a given speed, will produce less air flow as ambient temperature increases. As ambient temperature decreases, the opposite effect occurs; the MTG will produce more air flow. As air flow varies, more or less cooling is provided to the PSOFC, causing a resultant change in stack temperature. It is desirable to maintain an even stack temperature, because variations in stack temperature cause variations in voltage and efficiency.

Given that this system design has air flow that bypasses the stack, and MTG compressor air flow is varying due to ambient temperature, adjusting the module bypass valve (MBV) to vary the amount of bypassed air should able to compensate for changes in total air flow and provide a steady air flow through the stack. The MBV, however, is a large high-temperature air operated valve without a reliable control mechanism to consistently position the valve.

A recuperator bypass valve was also included in the design to provide a means for controlling stack temperature. Bypassing power turbine exhaust air around the recuperator provides less heating to compressor air, and lowering the air temperature into the stack. Conversely, providing maximum recuperation raises the stack air inlet temperature. Lowering and raising stack air inlet temperature should lower and raise stack temperature. Bypassing the recuperator lowers overall system efficiency, however, by “dumping” thermal energy. An automatic stack temperature control algorithm for operation of the recuperator bypass valve has not been implemented.

4.2 Recommendations

Design the first PSOFC and MTG hybrid power system.

- Follow-on projects that provide an ideal match between the PSOFC and MTG should be developed. This can most easily be accomplished by increasing the PSOFC stack size, power and air flow requirements. A larger stack will mean a higher stack cost, but will result in lower dollars per kilowatt initial cost.
- The scope of this project should be expanded to retrofit an inverter system for the DC generated power. This will demonstrate the ability to operate in a commercial application, and provide additional operational information on the effects of grid transients and outages on PSOFC / MTG operation.
- Follow-on projects in the design for MTG power should include provision to supply power to an external load, and the ability to parallel with the utility grid.

Demonstrate that the integrated system can be manufactured, started, operated, and shut down within design parameters.

- Repair the stack by replacing Row 2, and observe improved power and efficiency following restart. Repair is in progress.
- The recommendations for Objective 1 to better match the PSOFC and MTG will also result in improvements in power and efficiency.

Provide operational information and experience on the performance characteristics of the integrated design and identify problem areas to be resolved with improvements in follow-on designs.

- The variation in air flow due to ambient temperature may be unique to a PSOFC / MTG design with a dual-shaft MTG. Similarly, the mismatch between PSOFC air requirements and MTG air supply required the inclusion of the MBV in the design. Future designs with better matched PSOFC and MTG sizes will not likely include an MBV in the design, and it will not be available for temperature control.
- Follow on designs should incorporate a single-shaft MTG, which may alleviate the variations in air flow with ambient air temperature. As air temperature increases, the control system can electrically reduce the load on a single-shaft MTG, allowing turbine speed to increase and compensate for the decrease in air density. With decreasing ambient air temperature, MTG electrical load can be increased to slow turbine speed, and reduce air flow.

- This project should be operated for more than the planned 3000 hours. The useful stack life is estimated at 40,000 hours. Many longevity and endurance-related issues may be identified in long-term operation.

4.3 Commercialization Potential

This project has demonstrated a small power system (hundreds of kilowatts) that achieved the equivalent high efficiency of larger state-of-the-art combined cycle power systems (hundreds of megawatts). Small efficient power systems are well suited for distributed generation applications. Distributed generation provides power at or near its point of use, avoiding the high capital costs of power transmission and distribution. Distributed generation has not been widely implemented because smaller power systems have had lower efficiencies and higher pollutant emissions than larger centralized power generating systems.

4.4 Benefits to California

California needs more power generation to meet the demands of the growing population and economy. Power systems with high efficiency reduce fuel requirements and carbon dioxide emissions. Fuel costs are a significant portion of the cost to generate electricity; higher efficiency power systems use less fuel and reduce the cost of generation. This demonstration project of a hybrid PSOFC / MTG, has shown that high-efficiency power generation can be achieved in a small power system. Also, the pollutant combustion products, particularly NOx and carbon monoxide (CO), are extremely low with fuel cell generation because combustion of fuel is minimized.

This demonstration is the first step in DOE's Fossil Energy Program entitled Vision 21 that has a goal of developing small generating systems capable of 70% electrical energy efficiency. By co-funding this first of a kind demonstration, the Commission has aided in the development of advanced generation technology to meet California's need for clean and efficient power generation.

5.0 Glossary

AC	Alternating Current
BOP	Audio / Visual
C1	MTG Combustor No. 1 (SOFC Air Heater)
C2	MTG Combustor No. 2 (Gasifier Turbine Inlet)
CO	Carbon Monoxide
DC	Direct Current
DOE	U.S. Department of Energy
CICV	Compressor Inlet Check Valve
EBV	Exhaust Block Valve
EPRI	Electric Power Research Institute
FAT	Factory Acceptance Test
GEN/FSS	Generator / Fuel Supply System
HPAA	High Pressure Auxiliary Air
ICV	Inlet Check Valve
IRES	Ingersoll-Rand Energy Systems

kW	Kilowatts
kWe	Kilowatts of Energy
LPAA	Low Pressure Auxiliary Air
MBV	Module Bypass Valve
MTG	Micro Turbine Generator
NHMIX	97% Nitrogen, 3% Hydrogen Mix
NOx	Oxides of Nitrogen
NREC	Northern Research and Engineering Corporation
PAC	Process and Control
PIER	Public Interest Energy Research
PLC	Programmable Logic Controller
POC	Proof of Concept
psi	Pounds per Square Inch
PSOFC	Pressurized Solid Oxide Fuel Cell
PSOFC/MTG	Pressurized Solid Oxide Fuel Cell / Microturbine Generator
RD&D	Research, Development, and Demonstration

SCE	Southern California Edison Company
SOFC	Solid Oxide Fuel Cell
SCAQMD	South Coast Air Quality Management District
SSAA	Safety Stop Auxiliary Air
SSTOP	Safety Stop
STOP	Normal Stop
SWPC	Siemens Westinghouse Power Corporation
TMS	Thermal Management System
TSTOP	Turbine Stop
UCI	University of California at Irvine

Attachment 1 – Test Site Support Equipment

DC Load Controller with Power Conductors In and Out from Above

DC Load Bank

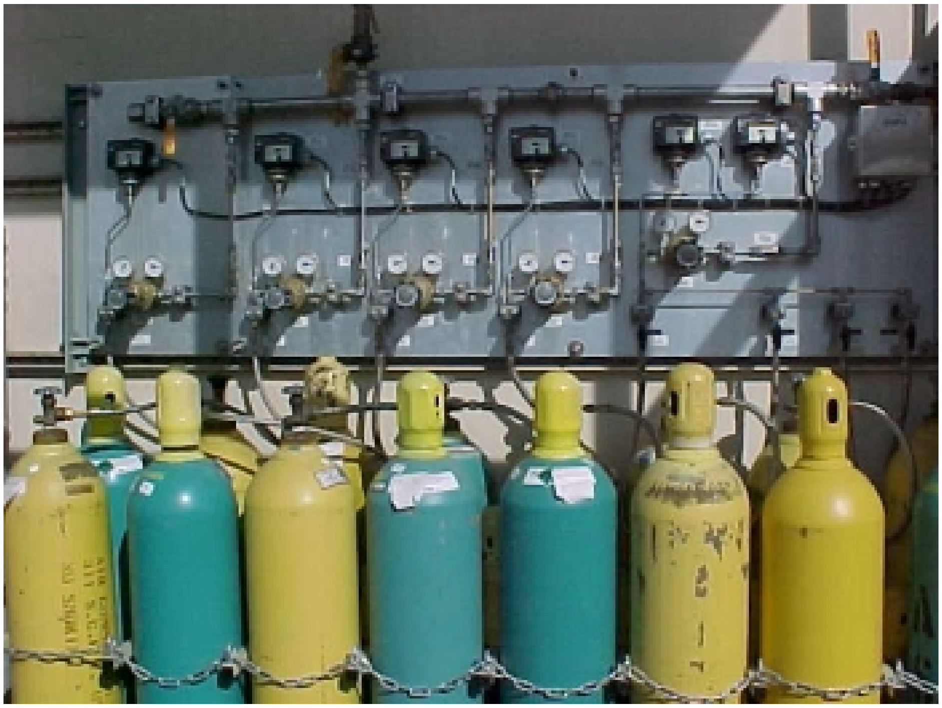
AC Load Bank with Integral Controls

Cable Tray for DC and AC Power Conductors – Wall Penetrations on the Left

Process Air Exhaust Duct (Right Vertical) from TMS Skid

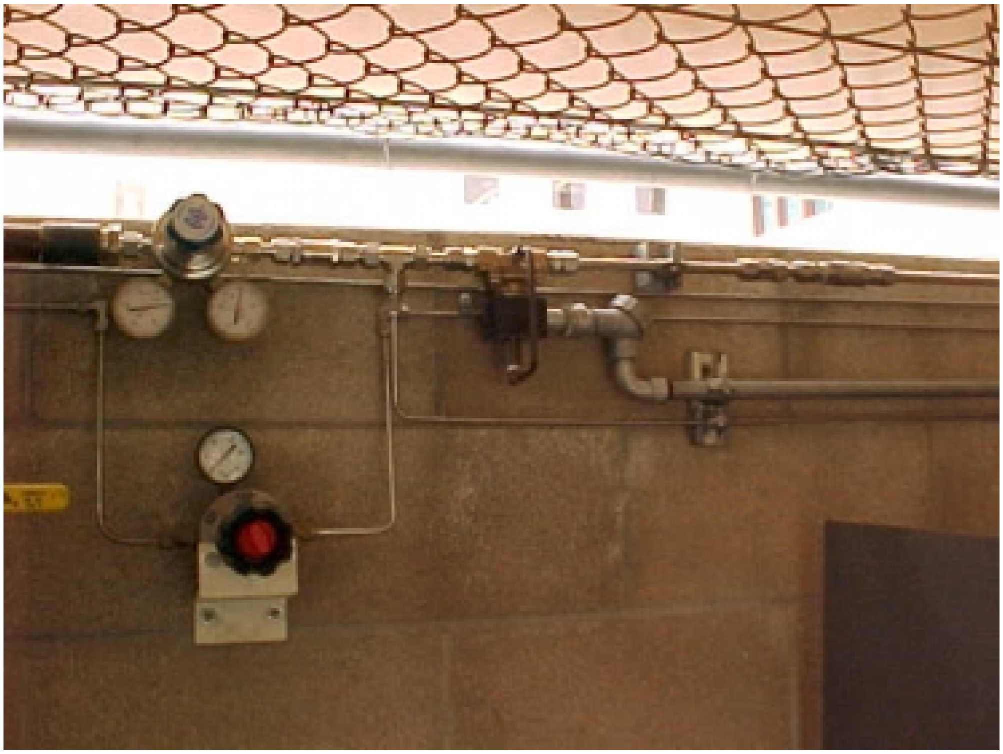
UPS Cabinet (left) with 1 of 2 Battery Pack Cabinets (right)

Natural Gas Desulfurization Tanks



Safety Stop Auxiliary Air Control Manifold and Air Cylinders

NHmix System Hydrogen Regulator, Solenoid Valve and Flow Control Orifice



NHmix System Nitrogen Regulator, Solenoid Valve and Flow Control Venturi

NHmix System Liquid Nitrogen Storage Tank

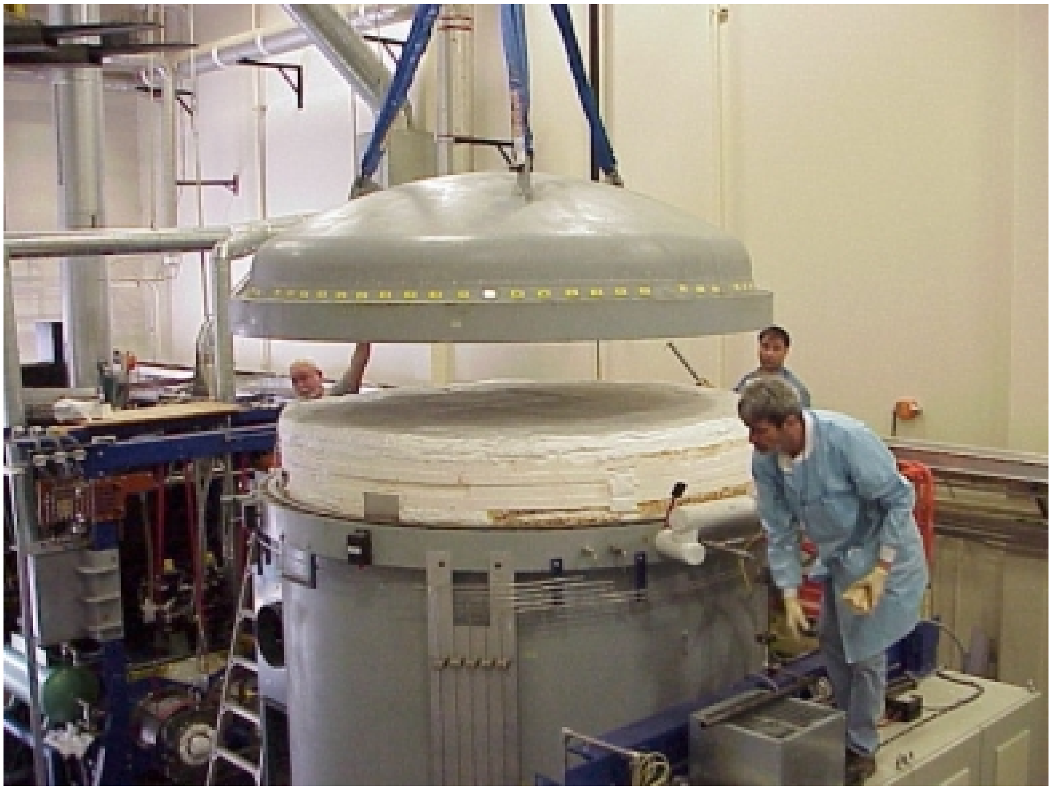
Attachment 2 – PSOFC and TMS Skid Installation

UCI Test Site Prior to PSOFC / MTG Installation
(following photos are taken from the upper level shown in this picture)

TMS skid (right) in place, PSOFC skid rolling in
(return of PSOFC after power lead failure)

PSOFC skid in place with shipping cover on pressure vessel
(initial installation). TMS skid located for later mating.

PSOFC skid with shipping cover removed. TMS in place.



Installing PSOFC pressure vessel head